



Snow Ensemble Uncertainty Project (SEUP): Quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling

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Introduction

The following supplemental information provides additional detail on the SEUP ensemble, which is comprised of 12 ensemble members, created by the combination of four different land surface models (LSMs, Text S1) and three different forcing datasets (Text S2).

35 Text S1 Land Surface Models (LSMs)

S1.1 Noah version 2.7.1 (Noah2.7.1)

Noah2.7.1 (Chen et al., 1996; Ek et al., 2003; Koren et al., 1999) is a LSM that has evolved through community efforts to simulate land surface temperature, snow depth, SWE, canopy water content, surface energy fluxes, water balance, soil temperature, and soil moisture based on the Oregon State University LSM (Mahrt and Pan, 1984). The Noah model has been
40 widely used in operational and research applications. For example, the Noah model has been adopted as the regional and global operational numerical weather prediction model at the NCEP and the 557th Weather Wing of the U.S. Air Force (formerly the Air Force Weather Agency). It also has been extensively evaluated in both the off-line mode (e.g., Chen et al., 1996; Mitchell et al., 2004) and the coupled mode (e.g., Chen et al., 1997; Ek et al., 2003). More detailed descriptions of the Noah physics and development are presented by Ek et al., (2003) and Koren et al. (1999). This study employs the Noah version 2.7.1, which
45 has a single canopy, and a single snow layer. The one-layer snow physical model simulates SWE as the residual of snowfall minus the sum of snowmelt and sublimation. Snowfall occurs whenever there is nonzero precipitation and the near surface air temperature is less than 0°C. Snow melting occurs when the temperature for canopy, ground, and snow is greater than the freezing point of water when SWE is greater than zero. Refreezing occurs when the layer temperature is less than the freezing point, and the liquid water content is greater than zero. Snow albedo representation uses a parameter -- maximum snow albedo
50 -- which is the upper bound of the fraction of reflected incoming shortwave radiation for deep snowpacks. Within Noah2.7.1, the maximum snow albedo can vary spatially but is temporally constant at given locations; these values were derived from Defense Meteorological Satellite Program (DMSP) imagery (Robinson and Kukla, 1985).

S1.2 Noah-MP version 3.6 (Noah-MP3.6)

The Noah-MP3.6 LSM (Niu et al., 2011) is built upon the legacy of the Noah model, but with new and multiple options for
55 selected processes. Most notably, Noah-MP3.6 performs separate energy budget calculations for the bare and vegetated portions of the grid cell; shortwave radiation is computed over the entire grid considering canopy gap probabilities, but longwave radiation, latent heat, sensible heat, and ground heat fluxes are computed separately over the vegetated area and bare ground. Noah-MP3.6 includes a four-layer soil model and up to three layers for snow, depending on snow depth. The revised snow scheme allows for snow compaction from the weight of overlying layers and melt metamorphism. Snow cover fraction
60 is computed as a function of snow depth, ground roughness length, and snow density (Niu & Yang, 2007). Noah-MP3.6 has two options for calculating snow surface albedo: the Biosphere-Atmosphere Transfer Scheme (BATS; (Yang et al., 1997) and

a Canadian Land Surface Scheme (CLASS; (Verseghy, 1991). CLASS is used here, which computes snow albedo based on the albedo of fresh snow and the age of the snow. For partitioning between rain and snow, Noah-MP3.6 has three options. Two options are simple comparisons of air temperature versus the freezing temperature ($T_{\text{air}} < T_{\text{frz}} + 2.2\text{K}$ and $T_{\text{air}} < T_{\text{frz}}$). The third option uses a function based on air temperature where the fraction of snow decreases between 1° and 2°C (Jordan, 1991), which is used in this study. Niu et al. (2011) performed offline comparisons for Noah and Noah-MP3.6 for two separate field sites and showed that Noah-MP3.6 improves the simulation of SWE, snow depth, density, and snow skin temperature. Compared with Noah, Noah-MP3.6, allows for the retention of meltwater within the snowpack and the refreezing of melt water, which improves the simulation of snow evolution during the melting season.

70 **S1.3 Catchment LSM version Fortuna 2.5 (CLSM-F2.5)**

The Catchment version used in this study is the Fortuna 2.5 version used in the Modern-Era Retrospective Analysis for Research and Applications (MERRA) with improved land surface variables (MERRA-Land; Reichle et al., 2011). The Catchment LSM (CLSM) shares the model development legacy with the Mosaic LSM (Koster and Suarez, 1996), which has been enhanced by adding a shallow groundwater module and by using a catchment-based approach (Koster et al., 2000). The basic computational unit of CLSM-F2.5 is the hydrological catchment (a.k.a., watershed) rather than a uniform latitude-longitude grid cell. It uses hydrological catchments as tiles with boundaries defined by topography. Each catchment is separated into three distinct and dynamically varying subareas: a saturated region, an unsaturated region, and a wilting region, which allows the sub-grid scale simulation of differing energy and water budget partitioning based on the moisture state. For ease of model intercomparison, however, the CLSM-F2.5 is used on a regular latitude-longitude grid in this study.

80 CLSM-F2.5 includes a three-layer snowpack model that incorporates snow physics including densification, snowmelt, refreeze, and snow insulating properties (Lynch-Stieglitz, 1994). The prognostic state variables for each of the three layers include SWE, snow cold content, and snow depth. The model uses an important parameter, SWE_{min} , which describes the minimum SWE that must be present per unit surface area before the model considers the surface to be snow covered. In the SEUP runs, SWE_{min} is set to 0.013 kg/m^2 . When there is surface melt or when rain falls on existing snow, water can percolate into the lower snow layers, where it may refreeze. Each layer of newly-fallen snow is initially given a density of 150 kg-m^{-3} , which increases as the snow ages. Snow surface albedo is treated with different reflectance values for the visible (VIS) and near-infrared (NIR) radiation bands, with reductions in albedo implemented by both vegetation masking and fractional snow cover (Stieglitz et al., 2001).

S1.4 Joint UK Land Environment Simulator (JULES)

90 The Joint UK Land Environment Simulator (JULES; Best et al., 2011; Clark et al., 2011) is based on the Met Office Surface Exchange Scheme (MOSES; Cox et al., 1999; Essery et al., 2003). This land surface model has been coupled to an atmospheric global circulation model, as done at the Hadley Center for Climate Prediction and Research (Blyth et al., 2006), or run in stand-

alone mode driven by forcing data. In the zero-layer snow model, used in this study, snow processes are incorporated in the top layer of the soil. Snow is given as a constant thermal conductivity of $0.265 \text{ W m}^{-1} \text{ K}^{-1}$ and a constant density of 250 kg m^{-3} . When snow remains on the ground, the surface skin temperature is not allowed to exceed 0°C , and the heat flux used to melt snow is diagnosed as the residual in the surface energy balance. Melting water from snow is directly partitioned into soil infiltration and runoff; there is no freezing of liquid water in snow. In this study, the diagnostic snow albedo parameterization option is selected (consistent with the operational configuration at the Met Office, Parallel Suite 41 (PS41)) which only uses snow depth and cannot represent the impacts of snow aging on the surface albedo. A detailed explanation can be found in Essery et al. (2003).

Text S2 Forcing datasets

S2.1 Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2)

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2; (Gelaro et al., 2017; Molod et al., 2015) is the long-term global reanalysis produced by NASA's Global Modeling and Assimilation Office (GMAO) that assimilates in situ and satellite observations into a global atmospheric model. It spans the satellite observing era (from 1980 to the present) with a regularly-gridded, homogeneous record of the global atmosphere, and improved land surface representation (i.e., the use of observation-based precipitation to force the land surface.) MERRA2 has a native spatial resolution of 0.5° latitude by 0.625° longitude (roughly 50 km).

S2.2 Global Data Assimilation System (GDAS)

The GDAS (Global Data Assimilation System; Derber et al., 1991) is the global, operational atmospheric analysis system based on the operational Global Forecasting Systems (GFS) developed at the Environmental Modeling Center (EMC) of the National Oceanic and Atmospheric Administration (NOAA) / National Centers for Environmental Prediction (NCEP). GDAS assimilates in situ and satellite observations into an atmospheric model for the purpose of initializing weather forecasts. The GDAS model grids have been upgraded from roughly 80km (since 2000), ~60km (Oct. 2002), ~38km (Jun. 2005), 27km (Jul. 2010), to ~13km (January 2015).

S2.3 European Centre for Medium-Range Weather Forecasts (ECMWF)

The European Centre for Medium-Range Weather Forecasts (ECMWF; Molteni et al., 1996) data is obtained from the operational, global analysis products. The model assimilates early in-situ surface observations as well as modern high-resolution satellite datasets. In this study, the operational real-time data from the ECMWF-Integrated Forecast System (IFS) are used; the meteorological fields are provided on a 0.25 -degree grid (roughly 25 km) at a 3-hour interval, and generated by assimilating available atmospheric observations every 12 hours into a forecast model with surface meteorological fields (e.g., precipitation and radiation), which are diagnosed from the model output (Dee et al., 2011; Flemming et al., 2015).

Table S1: Configuration of the SEUP model configurations used in this study. Note that all have a 5-km resolution with a 15-minute timestep using forcing from MERRA2, GDAS, and ECMWF. The model domain covers all of North America (24.9°N to 71.9°N and 168.6°W to 51.9°W).

LSMs	# of soil layers	# of snow layers	Dynamic vegetation model	Precipitation Partitioning	Snow albedo Parameterization	Snowpack energy balance	Sub-grid scheme
Noah 2.7.1	4	1	No	Snow for $T_{air} < 0^{\circ}\text{C}$, rain otherwise	Age of snow	Atmospheric skin interaction	N/A
					Fresh snow albedo	Liquid-water refreezing	
					Fractional snow cover	Conduction between layers	
					Vegetation masking	✓	
Noah-MP3.6	4	3	Yes	Jordan's scheme (Jordan, 1991)	Age of snow	Atmospheric skin interaction	Semi-tile vegetation and bare soil for the turbulence transfer
					Fresh snow albedo	Liquid-water refreezing	
					Fractional snow cover	Conduction between layers	
					Vegetation masking	✓	
CLSM F-2.5	3	3	No	Snow for $T_{air} < 0^{\circ}\text{C}$, rain otherwise	Age of snow	Atmospheric skin interaction	Each grid box's soil hydrology is separated into a saturated region, an unsaturated region, and a wilting region
					Fresh snow albedo	Liquid-water refreezing	
					Fractional snow cover	Conduction between layers	
					Vegetation masking	✓	
JULES	4	1	No	Snow for $T_{air} < 0^{\circ}\text{C}$, rain otherwise	Age of snow	Atmospheric skin interaction	A separate energy balance is calculated for each surface type
					Fresh snow albedo	Liquid-water refreezing	
					Fractional snow cover	Conduction between layers	
					Vegetation masking	✓	

Table S2: Individual mountain range areas based on Wrzesien et al. (2018).

Mountain range	Area (km ²)
1. Alaska	187000
2. Appalachian	179000
3. Brooks	236000

4. Cascades	197000
5. Coast	242000
6. Great Basin	207000
7. Mackenzie	551000
8. Rockies, Canadian	656000
9. Rockies, USA	702000
10. Sierra Nevada	64000
11. Torngat	42000
12. Total Mountainous areas	3250000
13. Total Non-Mountain areas	15190000

130 **Table S3:** Individual snow class range areas based on Liston & Sturm (2014).

Snow class range	Area (km ²)
1. Tundra	4640000
2. Taiga	3070000
3. Maritime	1640000
4. Ephemeral	3970000
5. Prairie	3530000
6. Warm forest	910000
7. Ice	50000

Table S4: Land cover range areas.

Land cover range	Area (km ²)
1. Forested	6550000
2. Non-forested	11920000

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